Next-Generation Optical Disc Technologies

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High-capacity optical discs including CDs, DVDs, and the Blu-ray Disc™ (Note 1) are now widely used as recording media for various purposes, and there is growing demand for a next-generation optical disc in the enterprise market that can store information for long periods and offer enhanced environmental robustness in addition to large-capacity storage. However, as high-density recording utilizing shorter-wavelength light sources such as the blue-violet laser for Blu-ray Disc™ reaches its performance limit, new technologies other than shortening of the wavelength are required for the next-generation optical disc, including multilayer recording, holographic data storage, near-field recording, and so on.

To fulfill these requirements in the enterprise market, Toshiba has developed novel holographic data storage (Note 2) technologies for practical application comprising a temperature compensation technology and a vibration compensation technology for use during the recording process.

1 Introduction

Optical discs have increased in storage capacity, from CDs to DVDs and then to Blu-ray discs (**Figure 1**). Each succeeding generation has adopted the basic scheme of shortening the wavelengths of the laser light sources specified by the respective optical disc standards to achieve higher-density recording. This is an effective method because the spot diameters of recording/reproducing light are proportional to their wavelengths. The next-generation optical discs that will succeed the above three generations of optical disc standards are known as fourth-generation optical discs. These discs began to be actively researched around the early 2000s when optical disc systems using blue-violet lasers were first developed. Additionally, currently a variety of large-capacity optical disc technologies including near-field recording, super-resolution recording, multilayer recording, and holographic data storage are being researched.

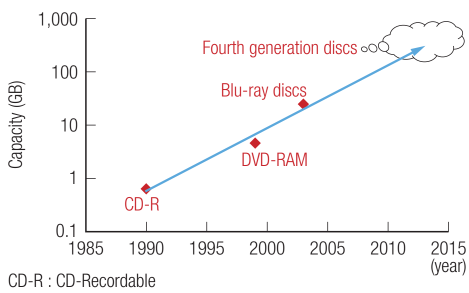


Figure 1. Trends in optical discs — Since the emergence of CD-Rs, the capacity of recordable optical discs has been rising at a pace of approx. ten times larger per ten years.

However, none of these types adopt the basic scheme of shortening the wavelengths of laser light sources (i.e., the use of ultraviolet lasers), instead allowing the use of blue-violet lasers as light sources as is done in the third generation of optical discs (i.e., Blu-ray discs). Reasons for this include the high rate of absorption of conventional optical elements in the ultraviolet region and the immaturity of semiconductor laser technologies. With respect to these points, fourth-generation optical discs differ from the previous generations and require a shift in approach so great as to constitute a paradigm shift.

(Note 1) Blu-ray Disc™ and Blu-ray™ are trademarks of the Blu-ray Disc Association.

(Note 2) Technology for recording data in the form of interference fringes occurring three-dimensionally from two overlaid beams of light—a reference beam and a signal beam—irradiated concurrently onto a recordable medium

This report presents an overview of techniques for increasing capacity as well as information on the technologies that Toshiba has developed for holographic data storage. We will also describe the market prospects while discussing how the areas of application of conventional optical discs including recorded music, standard definition video, high-definition video, and other such data will change in the next generation.

2 Trends in Technologies for Larger Capacity

Methods to achieve larger capacity based on Blu-ray disc technologies can be roughly divided into two types: reducing recording/reproducing light spot sizes and improving volumetric utilization of media (**Figure 2**). Methods for forming finer recording marks by reducing recording/reproducing spot sizes include super-resolution recording and near-field recording. Both technologies reduce spot sizes; super-resolution recording does so by using recordable media with special layers while near-field recording uses special objective lenses (solid immersion lenses). Meanwhile, methods for achieving larger storage capacity by increasing the space used to record data as per the entire volumetric space of the media include multilayer recording and holographic data storage.

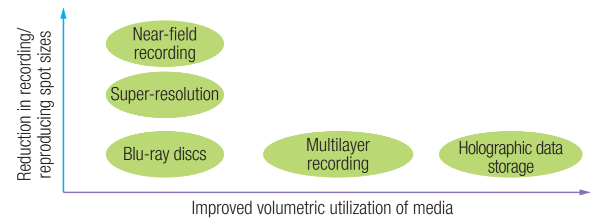


Figure 2. Technical solutions for next-generation optical disc — Techniques for increasing capacity are of two types: achieving higher density by reducing recording/reproducing spot sizes and achieving higher efficiency by increasing the rate of media's volumetric space used to record data.

For next-generation optical discs, relatively little margin remains for realizing higher density by reducing recording/reproducing spot sizes, since as mentioned previously shorter wavelengths of light sources cannot be expected. On the other hand, since the volumetric utilization of layers in recording media is currently low, increases in volumetric utilization may have greater potential for achieving larger capacity. In particular, multilayer recording is a direct extension of current technology, and the structure and construction of recording/reproducing systems using this type of recording will not deviate widely from current systems. By contrast, in holographic data storage the data recording method changes drastically—from recording on the basis of bits to recording on the basis of pages. In addition, the recording rationale between recording reflectivity change marks and recording interference fringes of page data images is fundamentally different. Therefore, the structure and construction of recording/reproducing drives will differ widely from current drives. For this reason, multilayer recording technology will require a relatively shorter development cycle, while holographic data storage technology will require a longer development cycle.

3 Multilayer Recording Technology

DVDs and Blu-ray discs record data as marks of sizes ranging from several to several tens of bits. These marks are recorded while concatenated in a spiral form within the recording layer plane. The amount of data within the recording layer is 4.3 to 4.7 GB for DVDs, and 25 to 33.4 GB for Blu-ray discs (**Figure 3**).

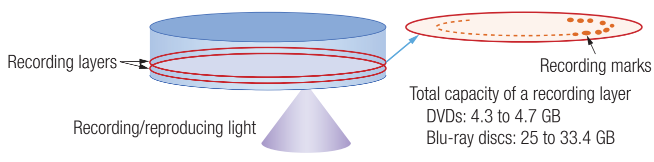


Figure 3. Structure of multilayer optical disc — Multilayer discs have multiple recording layers at different depths. The optical disc above has two layers.

Multilayer recording is a technology for achieving larger storage capacity by increasing the capacity per disc by adding multiple recording layers to the side used to record and reproduce data. For DVDs, write-once dual-layer discs (DVD-R DL) have been commercialized. As for Blu-ray discs, dual-layer and triple-layer discs have been commercialized in both write-once and rewritable types. Their maximum capacity is 100 GB.

As one characteristic of multilayer discs is that recording/reproducing light is irradiated from one side of the disc to conduct recording or reproduction for any one of the multiple layers, multilayer discs are designed such that the recording layers closer to the disc surface (the lower layer of the two in Figure 3) are semi-transparent, allowing an adequate amount of light to reach the layers far below the surface of the disc.

Meanwhile, development of technologies to increase the number of recording layers is being pursued. For Blu-ray discs, multilayer discs with up to four recording layers (total capacity of 128 GB) have been standardized. In addition, write-once recording discs with up to 16 recording layers (total capacity of 512 GB) have been reported at scientific conferences and similar events[1]. These multilayer recording discs require relatively small changes to adapt existing recording/reproducing systems for larger-capacity use. The more recording layers a disc has, the higher the degree of semi-transparency necessary in the layers to ensure that an adequate amount of light can penetrate the surface of the disc and reach the deepest layer. This poses potential problems such as a worse S/N ratio (signal-to-noise ratio) and increased crosstalk between the layers, but it is presumed that these difficulties can be overcome with schemes based on the parts or construction methods used for conventional recording/reproducing drives. Therefore, in terms of roadmap to market, multilayer disc projects can be accomplished in the relatively short term. For such cases, the multilayer level (i.e., the number of layers) must be optimized during the development process while paying attention to the needs for large capacity and product reliability.

4 Holographic Data Storage Technology

Figure 4 shows the rationale for recording and reproducing data with holographic data storage. Holographic data storage uses two beams of light—a signal beam and a reference beam—to record data. The data to be recorded is encoded on the signal beam in the form of a three-dimensional code (page data) and then irradiated onto the recordable medium. Concurrently, the recordable medium is irradiated by the reference beam, and the resultant three-dimensional interference fringes from the two overlaid beams are recorded as data. This allows the volumetric space of the recordable media to be made more fully available compared with the multilayer recording technology described in the previous section. To reproduce data, the signal beam used in recording is reproduced by irradiating only the reference beam onto the interference fringes. These interference fringes, which have a microstructure on the order of submicrons, require the relative variability between reference and signal beams to be small enough to allow for data to be recorded.

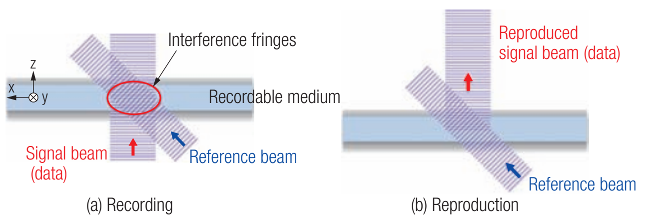


Figure 4. Recording and reproduction in holographic data storage — Interference fringes generated with two overlaid beams of light (i.e., the signal and reference beams) are recorded as data. To reproduce data, only the reference beam is irradiated onto the medium.

As a result, optical discs using this technology have advantages and drawbacks compared with conventional bit-recording optical discs. On the positive side, holographic data storage discs feature high transfer rates which enable a large amount of data (e.g., 1 Mb) to be recorded on the media at once, in addition to larger capacity achieved by allocating the full volumetric space of the media for data recording use. Negatives include deterioration of reproduced data depending on changes in the temperature of the recordable media and recording failures caused by vibrations occurring during recording. Overcoming these drawbacks is indispensable to commercialize holographic data storage technology. The following sections describe the technologies that Toshiba has developed to compensate for these drawbacks.

4.1 Technology to Compensate for Temperature[2]

In recent years, photopolymers, which are inexpensive and have good recording characteristics, have made inroads as holographic data storage media. However, since most photopolymers have a large coefficient of linear thermal expansion, they can cause deterioration of reproduced images when the temperature changes. To compensate for this deterioration, we have devised a new technique that uses closed-loop control to adjust the wavelengths of the reference beams for reproduction and their irradiation angles to the media.

For our temperature compensation algorithm, we have devised a method to detect wavelength and irradiation angle misalignments by the images reproduced with the intentionally slightly-tilted recordable medium (Figure 5). When the medium is slightly tilted when reproducing data, the intensity of only the thin bar-shaped regions is high in the reproduced images. By observing the radius of curvature and the intensity distribution in such regions, we can calculate the misalignments from the ideal wavelength and irradiation angle of the reference beam. In order to optimize the wavelengths and irradiation angles, we created a circuit that handles feedback control, including the capture of this misalignment signaling, wavelength and angle compensation, and the capture of images.

Figure 6 shows images compensated and captured with both our temperature compensation method and the conventional method. The images show that the conventional method leaves a clear unevenness in the brightness of the reproduced image, whereas the newly developed method is a significant improvement.

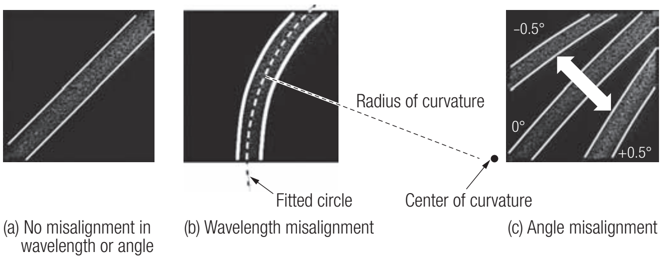


Figure 5. Reproduced images using temperature compensation — By tilting the medium slightly, wavelength or angle misalignment can be detected very precisely.

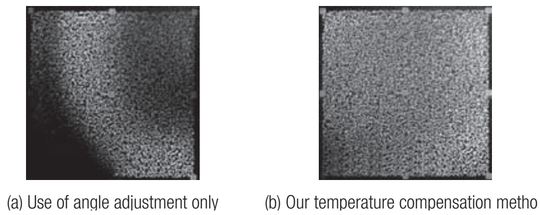


Figure 6. Reproduced images at temperature change of 25 K — Our temperature compensation method enables reproduction resistant to temperature changes. We conducted experiments under a temperature increased 25 K from the recording temperature.

4.2 Technology to Compensate for Vibration during Recording[3]

For DVDs and Blu-ray discs, the relative distance between the objective lens and the disc is controlled by a focus servo of a size on the order of submicrons. In holographic data storage, the control of the relative distance between the objective lens and the disc is insufficient because only signal beams—not the reference beams used to record data—pass through the objective lens. For this reason, we have developed technology to reduce the effects of vibration during recording rather than carrying out focus control.

During the first phase of development, we conducted experiments and analyses to study how reproduced images recorded under vibration are affected.

The reproduced images recorded under vibration at various directions to the medium are shown in (a) of Figure 7.

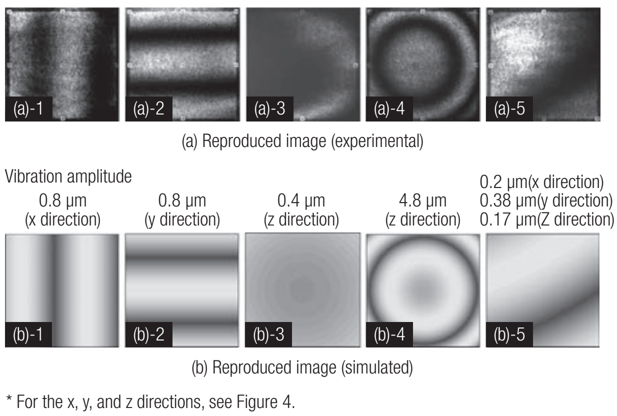
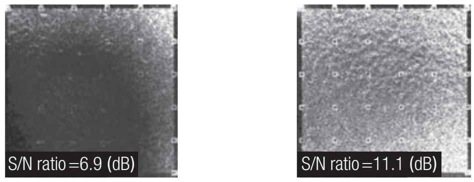


Figure 7. Experimental and simulated reproduced images recorded under continuous vibration — The reproduced images simulated in (b) precisely replicate the deterioration in the reproduced images in (a) caused by vibration of the medium.

The experiment with vibration of an amplitude on the order of submicrons revealed periodic unevenness in the brightness of images ((a)-1, 2, and 4) and an image darkened overall ((a)-3).

By understanding these phenomena to be the interference between the two holograms reproduced from the two interference fringes recorded at peak amplitude, we created analysis models to replicate these phenomena. Our simulated results with these models are shown in (b) of **Figure 7**. The numbering of the images in **Figure 7** is shared between (a) and (b) depending on the type of vibration applied. Our comparison of experiment and analysis results revealed similar image deterioration, confirming the validity of these analysis models.

After validating the analysis models, we determined that by preventing vibration from causing the two holograms to be overlaid during recording, image deterioration could be eliminated. Through such determination, we devised a method of substantially reducing the effects of vibration by intermittingly irradiating the recording beams based on the amount of relative displacement between the medium and the optical system. **Figure 8** shows the results of data recording under continuous application of a vibration of amplitude 0.4 μm. Using the new recording method showed a clear improvement in image (b) compared with (a) in which the new method was not used. Thus, we confirmed the effectiveness of this recording method.



(a) Recorded without compensation (b) Recorded with compensation

Figure 8. Comparison of reproduced images with and without vibration compensation — The new recording method improves the quality of reproduced images significantly by eliminating the effects of vibration.

5 The Market for Next-generation Optical Discs

The storage market has undergone remarkable changes over the past several years. It includes the emergence of tablet PCs without ODDs (optical disc drives) and PCs without HDDs as well as the market debut of SSDs (solid state drives). These trends have caused the ratio of ODDs installed in PCs to decrease overall. Looking at the entire market, we expect that the percentage of semiconductor-base storage will increase with respect to storage systems in the PC and consumer-oriented system segments.

On the other hand, due to the ever-growing amount of data handled by users, there is a general perception that the amount of data will continue to grow exponentially. As for where this data will be stored, we expect that there will be a move from storage on personally owned systems to network storage. In addition, the storage capacity of enterprise systems, as represented by cloud computing systems (Note 3), is expected to rapidly grow larger. For enterprise systems, effective management realized by specializing data handling based on accessibility, importance, and other such factors is required.

Therefore, selecting the storage device most suitable for each purpose is the key to successful system management. For example, it is not effective if data that is rarely accessed but has a high need for long-term storage is stored on an SSD, which allows for fast access but is relatively expensive. Rather than SSD or HDD storage, cost-effective management of this type of data can be achieved through offline management disconnected from the network, such as storage on an optical disc, which is excellent for long-term storage and has superior environmental resistance performance. In addition, removing the disc from the system and storing it in an offline environment leads to reduced energy consumption for long-term storage, thereby contributing to more environmentally friendly systems.

(Note 3) Services provided by servers on the Internet or networks of communication service providers

Thus we expect that the next-generation optical disc market will significantly evolve from primarily serving as a means of distributing media to consumers (e.g., music on CDs and movies on DVDs and Blu-ray discs) to serving as media for enterprise data archiving (long-term storage and recording). In addition to the above-mentioned technical changes, we can surmise that next-generation optical discs will significantly change their role in the market. Next-generation optical discs are therefore required to be built with specifications prepared for these market changes. To positively respond to this trend, we shall do so.

6 Conclusion

Above, we described the technical trends behind larger-capacity techniques for CD, DVD, and next-generation optical disc (i.e., fourth-generation optical discs to succeed Blu-Ray discs) technologies. We also reported that, as a technique to realize larger capacity, Toshiba has developed novel holographic data storage technologies for practical application. We also made projections about changes in the next-generation optical disc market, which we expect to shift from primarily targeting consumers to primarily targeting enterprise users.

Toshiba will continue to pursue the development of next-generation optical discs with a watchful eye to assess changes in technologies and target markets.

References

(1) Inoue, M. et al. 512GB recording on 16-layer optical disc with Blu-ray Disc based optics. Proc. of SPIE. 7730, 2010, 77300D-1–77300D-6.

(2) Usui, T. et al. Temperature Compensation Servo Algorithm for Holographic Data Storage. Jpn. J. Appl. Phys. 49, 2010, 08KD04-1–08KD04-2.

(3) Usui, T. et al. “Investigation and Reduction of Signal Deterioration Caused by Submicron Vibration on Holographic Data Recording”. Technical Digest of International Symposium on Optical Memory. Hualien, Taiwan, 2010-10, The Japan Society of Applied Physics (JSAP), The Magnetics Society of Japan (MSJ), and Optoelectronic Industry and Technology Development Association (OITDA). 2010, p.228–229.

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